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Transmission Through Ferrite Samples at Submillimeter Frequencies

by Clyde A. Morrison
Barbara J. Bencivenga
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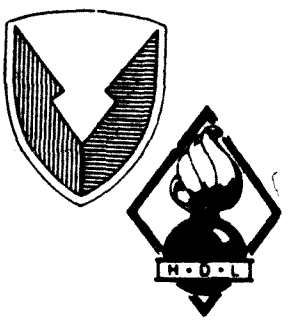

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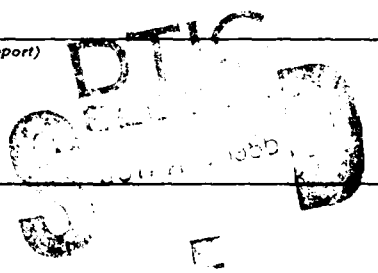

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A theoretical analysis is presented of the transmission spectra of thin magnetized ferrite slabs. The energy range chosen was $1 < \bar{\nu} < 120$ cm^{-1} (30 GHz < f < 3600 GHz). The magnetic field was assumed to lie in the plane of the ferrite slab, and the incident electromagnetic radiation was polarized parallel and perpendicular to the magnetic field. For measurements of the magnetic properties near resonance, we show that extremely stable sources are required. However, we show that meaningful measurements can be made far from magnetic resonances using a conventional Fourier transform spectrometer.

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CONTENTS

FIGURES

A-1

1. INTRODUCTION

Because of an increased technological interest in materials to be used in the submillimeter region and higher frequencies, it has become important to measure the properties of useful materials at these frequencies. The complex dielectric constant of a number of materials has been measured in the 4 to 20 cm^{-1} range,[1] but very little has been reported on the magnetic properties of ferrites or other ferromagnetic materials.

In this report we present a theoretical analysis applicable to the measurement of the magnetic properties of materials in the energy range 1 $cm^{-1} < \bar{\nu} < 120\ cm^{-1}$ (30 GHz < f < 3600 GHz). The analysis consists of an investigation of the transmission of a ferrite slab magnetized in the plane of the slab with the electromagnetic wave polarized parallel or perpendicular to the magnetic field. The direction of propagation is perpendicular to the plane of the slab.

The first case analyzed is for ferromagnetic resonance occurring in the range 3 $cm^{-1} < \bar{\nu} < 7\ cm^{-1}$. This range of energy is somewhat hypothetical for conventional ferrites because of the requirement of extremely large magnetic fields (50,000 gauss). Nevertheless, an investigation of resonance at these frequencies does illustrate the resolution requirements on any spectrum analyzer that might be used in the measurements. However, the resonance of hexagonal ferrites does occur at submillimeter frequencies for moderate fields, and the analysis given is useful for these materials. A number of antiferromagnetic materials have their resonances at very high frequencies and at moderate external magnetic fields. These materials have received little attention as to their possible application in the submillimeter region. This analysis should be useful with possibly slight modification.

The second aspect of this report is the investigation of the magnetic effects far from ferromagnetic resonance ($\bar{\nu} >> \bar{\nu}_{res}$). Because of the application of a number of ferrites at microwave frequencies, good quality materials are available in that frequency range. These materials have low internal fields, and magnetic resonance is determined predominately by the application of an external field. Little is known of the properties of these latter materials in the frequency band from 1 to 20 cm^{-1}. The results predicted here use the values characterizing the ferrite at X-band and may be altered when such quantities as the dielectric constants are better determined.

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[1] George J. Simonis, Joseph P. Sattler, Terrance L. Worchesky, and Richard P. Leavitt, Characterization of Near-Millimeter Wave Materials by Means of Non-Dispersive Fourier Transform Spectroscopy, J. Infrared and Mill. Waves, 5 (1984), 57. (This reference reports the measured complex dielectric constant of TT2-111, the prototype ferrite used here.) See also George J. Simonis, Index to the Literature Dealing with the Near-Millimeter Wave Properties of Materials, Int. J. Infrared and Mill. Waves, 3 (1982), 439 (170 articles referenced).

2. THEORY

In a previous report,[2] an expression for the effective permeability, μ_e, was derived for a lossless medium. In the appendix of that report, the expressions for μ and κ were derived using Gilbert's[3] damping to give ($e^{-i\omega t}$ assumed time dependence)

$$\mu_{\pm} = 1 \mp \frac{\gamma 4\pi M}{\omega \pm i\gamma\Delta H \mp \gamma H_o} \quad , \tag{1}$$

$$\mu_{\pm} = \mu \pm i\kappa \quad ,$$

with

$$B_x \pm iB_y = \mu_{\pm}\left(H_x \pm iH_y\right)$$

and

$$B_x = \mu H_x + i\kappa H_y \quad , \quad B_y = \mu H_y - i\kappa H_x \quad ,$$

where

$4\pi M$ = the saturation magnetization,

γ = the gyromagnetic ratio,

ΔH = one-half the full line width at half maximum,

H_o = the external field along the z direction.

The $\mu_{\pm}$ in equation (1) corresponds to the permeability seen by right or left circular polarized waves propagating in the direction of the external field in an infinite medium. The experimental results are usually given as the full line width at half maximum, δH. Then ΔH in equation (1) is given by $\Delta H = \delta H/2$. If the external magnetic field is applied along a principal axis, the magnetic anisotropy can then be taken into account by letting $H_o \rightarrow H_o + H_A$, where H_A is the effective anisotropy field.[4] If we assume that we have a

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[2] Clyde A. Morrison, A. F. Hansen, and K. M. Sorenson, Theoretical Analysis of Nonreciprocal Electromagnetic Surface Wave Devices, Harry Diamond Laboratories, HDL-TR-2017 (September 1983).

[3] T. A. Gilbert, Armour Research Foundation, Rept. No. 11 (25 January 1955).

[4] W. H. Von Aulock, ed., Handbook of Microwave Ferrite Materials, Academic Press, New York (1965), 464.

plane wave with E parallel to the field H_o and in the plane of a slab of thickness, a, the relative amplitude of the transmitted wave is

$$T_{a\parallel} = \frac{e^{-ika}}{\cos\left(ka\sqrt{\varepsilon\mu_e}\right) - \frac{i}{2}\left(z_e + \frac{1}{z_e}\right)\sin\left(ka\sqrt{\varepsilon\mu_e}\right)} \quad , \tag{2}$$

where

$$k = \frac{\omega}{c} \quad ,$$

$$k = 2\pi\bar{\nu} \quad ,$$

$$\mu_e = \frac{\mu^2 - \kappa^2}{\mu} \quad ,$$

$$z_e = \sqrt{\mu_e/\varepsilon} \quad ,$$

and ε is the dielectric constant. In equation (2), k is always real, but ε and μ_e are, in general, complex.

In the derivation of equation (2), the slab is assumed to lie in the y-z plane and to be of thickness a. The wave equations for E_z in the two regions were taken as

$$\frac{d^2}{dx^2} E_z = -k^2 E_z \quad \text{in free space} \quad ,$$

$$a < x \quad , \quad x < 0 \quad ,$$

and (3)

$$\frac{d^2}{dz^2} E_z = -k^2 \varepsilon \mu_e E_z \quad \text{in the ferrite} \quad ,$$

$$0 < x < a \quad .$$

The result given in equation (2) was obtained by using the general solution to equation (3) and boundary conditions on E_z and H_y at the interfaces $x = 0$ and $x = a$. The amplitude transmission coefficient for plane waves polarized with $E \perp H_o$ (the z-axis) is obtained by letting $\mu_e \to 1$ in equation (2), or

$$T_{a\perp} = \frac{e^{-ika}}{\cos\left(ka\sqrt{\varepsilon}\right) - \frac{i}{2}\left(\sqrt{\varepsilon} + \frac{1}{\sqrt{\varepsilon}}\right)\sin\left(ka\sqrt{\varepsilon}\right)} \quad . \tag{4}$$

In the derivation of equation (4), the field E was assumed to be polarized along the y-direction, and the wave equation inside the ferrite is

$$\frac{d^2}{dx^2} E_y = -k^2 \varepsilon E_y \quad . \tag{5}$$

In all the equations given above, ε and μ_e are, in general, complex.

Measurements are generally made on the power transmitted which is $|T_a|^2$ in either equation (2) or (4). If we assume that the thickness, a, is very small, then

$$\cos\left(ka\sqrt{\varepsilon\mu_e}\right) \sim 1 \quad ,$$

and

$$\sin\left(ka\sqrt{\varepsilon\mu}\right) \sim ka\sqrt{\varepsilon\mu_e} \quad .$$

And, from equation (2),

$$T_a = \frac{1}{1 - \frac{i}{2}\left(\varepsilon + \mu_e\right)ka} \quad . \tag{6}$$

The power transmitted, $T_p = |T_a|^2$, becomes

$$T_p = \frac{1}{1 + \left(\varepsilon_2 + \mu_{e2}\right)ka} \quad , \tag{7}$$

where

$$\varepsilon = \varepsilon_1 + i\varepsilon_2 \quad ,$$

and

$$\mu_e = \mu_{e1} + i\mu_{e2} \quad .$$

The effective permeability, μ_e, given in equation (2) is the permeability as seen by a plane wave propagating in the x-y plane polarized with E in the z direction. Using the result of equation (1) and the expression for μ_e given in equation (2), we obtain

$$\mu_e = \frac{\left(H_1 - B\right)\left(H_1 + B\right) + \Delta H^2 + i(2B)\Delta H}{\left(H_1 - H_2\right)\left(H_1 + H_2\right) + \Delta H^2 + i(B + H)\Delta H} \quad , \tag{8}$$

where

$$H_1 = \frac{\omega}{\gamma} \quad ,$$

$$H_2 = \sqrt{BH} \quad ,$$

$$B = H + 4\pi M \quad ,$$

$$\gamma = \left[8.795 \times 10^6 \text{ radians/(second-oersted)}\right] g \quad ,$$

and

$$g = \text{effective g factor (generally ~2)} \quad .$$

The complex index of refraction, n, is given by

$$n = \sqrt{\varepsilon \mu_e} \quad ,$$

$$n = n_1 + i n_2 \quad ,$$

$$\varepsilon = \varepsilon_1 + i\varepsilon_2 \quad ,$$

and

$$\mu_e = \mu_{e1} + i\mu_{e2} \quad .$$

The components of the complex μ_e and n are shown in figure 1 for an applied field of 50,000 oersteds. The parameters of the ferrite (see TT2-111, Von Aulock[4]) are

$$4\pi M_s = 5000 \text{ gauss} \quad ,$$

$$\Delta H = 67.5 \text{ oersteds (experimental full half power width = 135.0 oersteds)},$$

$$g = 2.08 \quad ,$$

$$\varepsilon_1 = 12.5 \quad ,$$

and

$$\varepsilon_2 = 0.0125 \quad .$$

[4] W. H. Von Aulock, ed., Handbook of Microwave Ferrite Materials, Academic Press, New York (1965), 464.

The linewidth of the ferrite chosen for figure 1 is characteristic of the linewidths observed at microwave frequencies. It is quite possible that this width will not change significantly at higher frequencies. Thus, to observe resonance directly at these high frequencies ($\bar{\nu} > 5$ cm^{-1}), the spectrometer will have to have a very high resolving power. Resonance could most readily be directly observed with a stabilized oscillator and by sweeping the magnetic field through resonance, as is done at microwave frequencies.[5]

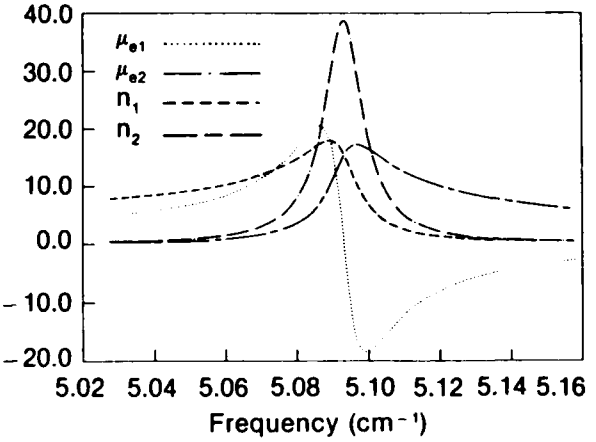

Figure 1. Ferromagnetic resonance for a plane wave in an infinite medium characterized by $\mu_e = \mu_{e1} + i\mu_{e2}$, $\varepsilon = \varepsilon_1 + i\varepsilon_2$, $n = \sqrt{\varepsilon\mu_e} = n_1 + in_2$. Parameters characterizing ferrite TT2-111 are $4\pi M_s = 5000$ gauss, $\delta H = 135$ oersteds, $g_{eff} = 2.08$, $\varepsilon_1 = 12.5$, and $\varepsilon_2 = 0.0125$.

The results shown in figure 1 are for an infinite medium. When the sample is of finite extent, the boundaries of the ferrite affect the resonance condition. In fact, for different shaped samples whose dimensions are small compared to the wavelength, Kittel[6] shows that the resonance condition varies considerably with the shape of the sample. Using the result of equation (8), we obtain

$$\mu_{e2} = \frac{4\pi M\left(B^2 + H_1^2 + \Delta H^2\right)\Delta H}{\left(H_1^2 - H_2^2 + \Delta H^2\right)^2 + \left(B + H\right)^2\Delta H^2} \quad . \tag{9}$$

The result given in equation (9) was substituted into equation (7), and the minimum values of T_p were found for a range of slab thicknesses a, such that $ka < 1$. The increase in the linewidth of the power transmitted is shown in figure 2 for the same parameters used in the calculations of figure 1. As can be seen, the linewidth increases quite rapidly with slab thickness (slope ~ 10.0 cm^{-1}/cm). The frequency at resonance also shifts with slab thickness. This shift is important in determining the gyromagnetic ratio or, equivalently, the effective g value ($\gamma = g(1.3998 \times 10^6)$Hz/oersted).

The shift of the peak at maximum absorption is shown in figure 3 for the same range of thickness as shown in figure 2. Also, the same ferrite was chosen. For the ferrite chosen in figure 3, the shift in frequency at resonance is seen to be negligible for $a \lesssim 10$ μm. For thicker ferrite samples, the behavior near resonance becomes very complicated, and the extraction of the properties of the material that determine resonance is difficult or

[5] Joseph Nemarich, Measurement of Narrow Magnetic Resonance Linewidths, Harry Diamond Laboratories, HDL-TR-1246 (10 August 1964).

[6] C. Kittel, Introduction to Solid State Physics, Wiley and Sons, New York (1976).

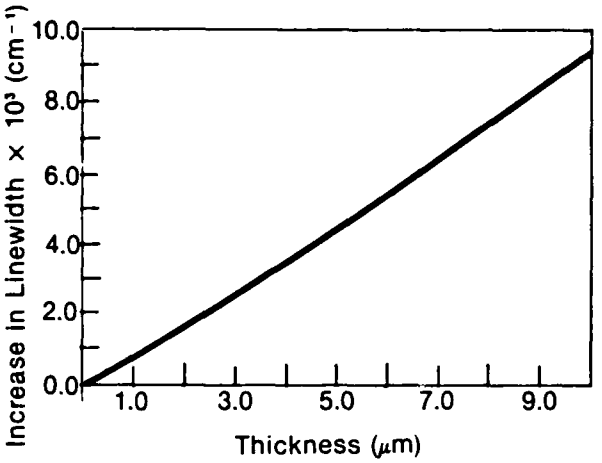

Figure 2. Increase in measured linewidth as a function of thickness of the ferrite slab. External magnetic field is 50,000 gauss. Parameters characterizing ferrite are given in figure 1.

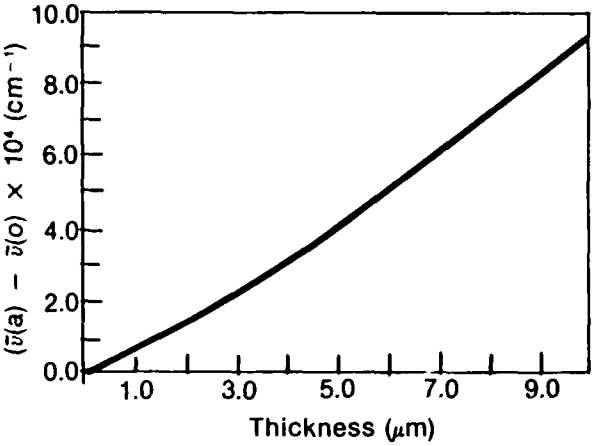

Figure 3. Shift in resonance frequency as a function of thickness of ferrite slab. External magnetic field, H_o, is 50,000 gauss. Parameters characterizing ferrite are given in figure 1.

impossible. To illustrate the effect of increasing thickness on the transmitted power through a ferrite slab, several thicknesses were chosen, and the results are shown in figures 4 through 8. All these figures are for the same ferrite (TT2-111). In figure 4, the ferrite thickness is chosen by using the results of figures 2 and 3. For a 2-μm-thick sample, the increase in linewidth is approximately 0.3 cm^{-1}, and the shift is approximately 2×10^{-3} cm^{-1}. This small shift is negligible, but the increase in linewidth may be significant, depending on the desired precision of the experimental results. Figure 5 gives the transmission of a 10-μm-thick sample as a function of frequency. Pronounced asymmetry of the resonance line has begun to appear due to an increase, at magnetic resonance, in the optical thickness of the sample. As the thickness is increased to 40 μm, the entire transmission becomes distorted so much that resonance behavior is obliterated, as shown in figure 6. Figures 7 and 8 are for 70- and 100-μm-thick samples and illustrate the complicated behavior of the transmission near ferromagnetic resonance. These latter results illustrate the difficulty, if not the impossibility, of extracting the prope ties of the ferromagnetic material near resonance if the samples are too thick.

For most of the ferrites developed for use at microwave frequencies, the external magnetic field required for resonance at submillimeter wavelengths ($5 < \tilde{\nu} < 100$ cm^{-1}) is very large ($H_o \sim 50{,}000$ oersteds in the previous examples). Such magnetic fields are unobtainable in most laboratories. Thus, it is important whether or not meaningful measurements can be made in the region $f >> \gamma(H_2^2 - \Delta H^2)^{1/2}$ (approximately the frequency of resonance in infinite media). For very high frequency (H_1 larger than all other quantities in equation (8)),

$$\mu_e \approx 1 - \frac{4\pi MB}{H_1^2} + i\,\frac{4\pi M\Delta H}{H_1^2} \quad , \tag{10}$$

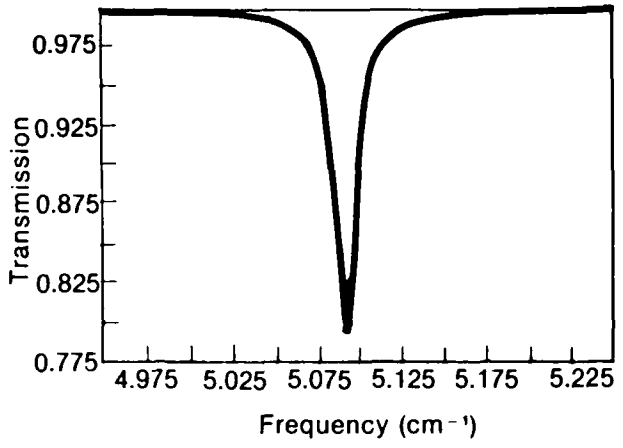

Figure 4. Power transmission coefficient for 2-μm-thick ferrite slab. External magnetic field, H_o, is 50,000 oersteds. Parameters characterizing ferrite are given in figure 1.

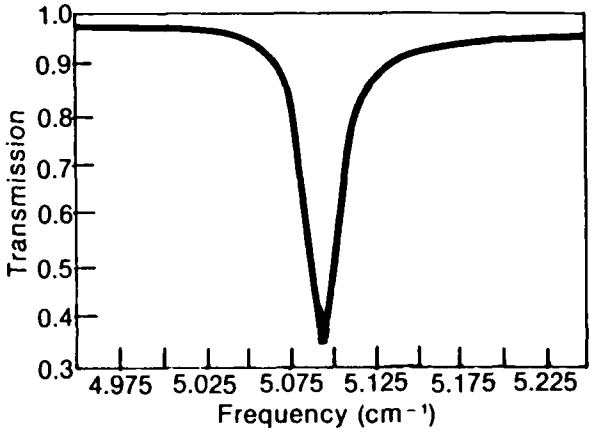

Figure 5. Power transmission coefficient for 10-μm-thick ferrite slab. External magnetic field, H_o, is 50,000 oersteds. Parameters characterizing ferrite are given in figure 1.

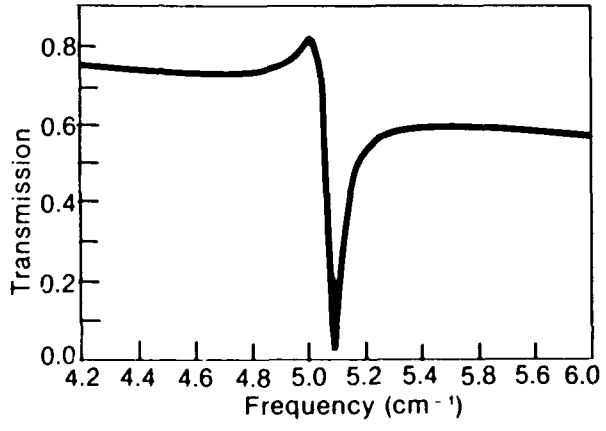

Figure 6. Power transmission coefficient for 40-μm-thick ferrite slab. External magnetic field, H_o, 50,000 oersteds. Parameters characterizing ferrite are given in figure 1.

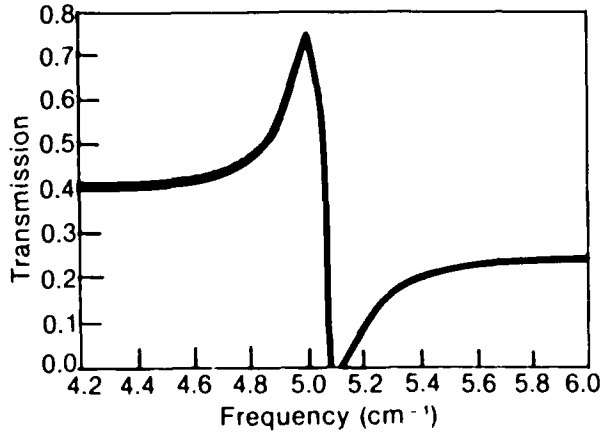

Figure 7. Power transmission coefficient for 70-μm-thick ferrite slab. External magnetic field, H_o, is 50,000 oersteds. Parameters characterizing ferrite are given in figure 1.

and the index of refraction is much smaller than when near ferromagnetic resonance. Thus, much thicker slabs of ferrite can be used in the measurements at these higher frequencies. Even with thicker samples, the frequency intervals between maxima and minima of the transmission ($\Delta\bar{\nu} \sim 1/an_1$) are resolvable so that the complex index of refraction can be extracted from the data. Further, the complex dielectric constant can be measured using the result given in equation (4) ($T_{p\perp} = |T_{a\perp}|^2$, and this result can be used to extract μ_e by using measurements of $T_{p\parallel}$ given by equation (2), $T_{p\parallel} = |Ta_{\parallel}|^2$).

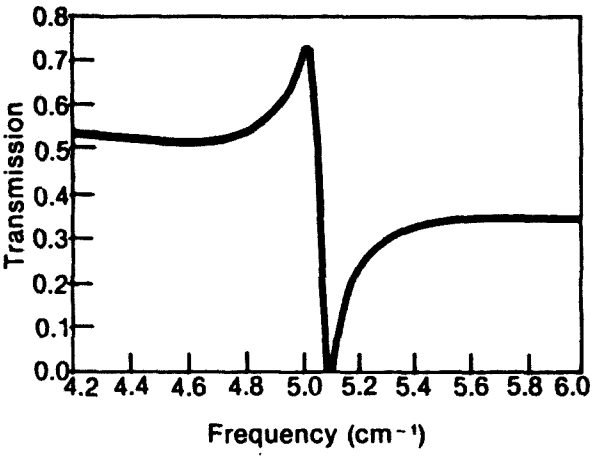

Figure 8. Power transmission coefficient for 100-μm-thick ferrite slab. External magnetic field, H_o, is 50,000 oersteds. Parameters characterizing ferrite are given in figure 1.

For the ferrite characterized in figure 1, the transmitted power was determined for a slab of thickness a = 1 mm using equation (4) and the results shown in figure 9. The effect of the periodic oscillations ("channel spectrum") is very evident. In the lower frequency range ($\bar{\nu} < 7$ cm^{-1}), the differences between $T_{p\parallel}$ and $T_{p\perp}$ are distinguishable. Below 2.5 cm^{-1}, ferromagnetic resonance effects are evident. Thus, in the range 2.5 cm$^{-1} < \bar{\nu} < 7$ cm^{-1}, the dielectric constant can be determined using the transmission curve, $T_{p\perp}$. At a higher frequency, $\bar{\nu} >$ 5 cm^{-1}, the dielectric losses increase significantly. The measured values of $\varepsilon_2(\varepsilon = \varepsilon_1 + i\varepsilon_2)$ for the ferrite TT2-111 are given in figure 9 as reported by Simonis et al.[1] The region $0 < \bar{\nu} < 7$ cm^{-1} is estimated, but the region $7 < \nu < 17.5$ cm^{-1} has been measured experimentally. The solid lines in figure 9 are approximate fits to the data in the two regions. The variation of ε^2 with ν in the region $0 < \bar{\nu} < 5$ cm^{-1} has been checked for the cases given in figures 4 through 8, and it has negligible effect. However, figure 10 shows the transmission through a slab of 1 mm with $\varepsilon^2 = 0.0125$, and figure 11 shows the results when the data of figure 9 are used. As can be seen, the effect of the increase in ε_2 with frequency is significant and must be considered in the higher frequency calculations. For the same thickness samples, the transmission was calculated for external magnetic fields of 10,000 and 15,000 oersteds, and the results are shown in figures 12 and 13. The range of frequencies for $\nu >> \gamma H$ ($\bar{\nu} > 5$ cm^{-1}), over which the two curves $T_{p\parallel}$ and $T_{p\perp}$ increase with magnetic field, is as would be expected from equation (10). With the results given in figures 11, 12, and 13 viewed as experimental data, it seems reasonable to assume that the parameters $4\pi M$ and γ can be

[1] George J. Simonis, Joseph P. Sattler, Terrance L. Worchesky, and Richard P. Leavitt, Characterization of Near-Millimeter Wave Materials by Means of Non-Dispersive Fourier Transform Spectroscopy, J. Infrared and Mill. Waves, 5 (1984), 57. (This reference reports the measured complex dielectric constant of TT2-111, the prototype ferrite used here.) See also George J. Simonis, Index to the Literature Dealing with the Near-Millimeter Wave Properties of Materials, Int. J. Infrared and Mill. Waves, 3 (1982), 439 (170 articles referenced).

determined by using equation (10) in conjunction with experimental data. The transmission coefficient for a 1-cm-thick sample (TT2-111) is shown in figure 14. Despite the complicated appearance of the curves, the effective index of refraction can easily be extracted from the data for the entire range of frequencies ($3\ cm^{-1} < \bar{\nu} < 6\ cm^{-1}$).

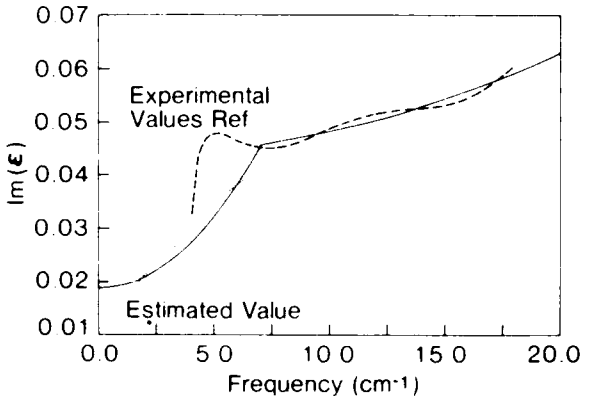

Figure 9. Experimental values of ε_2. The ε_2 values for 0 to 7.5 cm^{-1} are estimated, and the values $7.5 < f < 17.5\ cm^{-1}$ are reported by Simonis et al. Solid lines are approximate fits to the experimental data and are used in the computation.

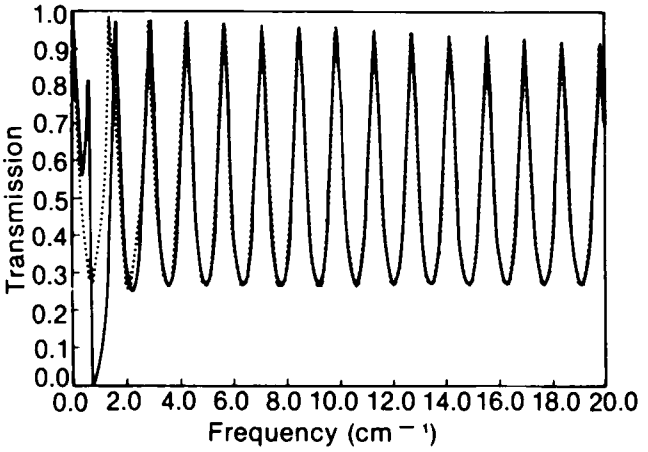

Figure 10. Power transmission coefficient ($E \parallel H_o$ solid, $E \perp H_o$ dotted) for 1-mm-thick sample. External field, H_o, is 5000 oersteds. Parameters characterizing ferrite are given in figure 1.)

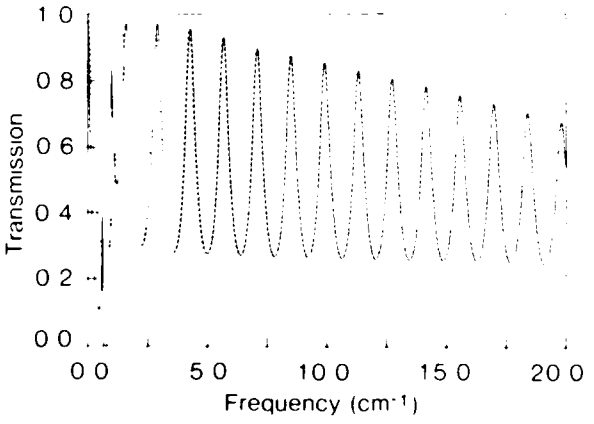

Figure 11. Power transmission coefficient ($E \parallel H_o$ solid, $E \perp H_o$ dashed) for 1-mm-thick sample. External field, H_o, is 5000 oersteds. Parameters characterizing ferrite are given in figure 1, except for value of ε_2. Values of ε_2 are taken from the fit to experimental data given in figure 9.

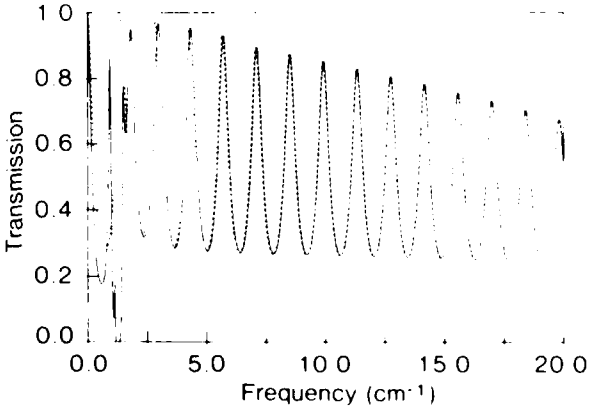

Figure 12. Power transmission coefficient ($E \parallel H_o$ solid, $E \perp H_o$ dashed) for 1-mm-thick sample. Magnetic field, H_o, is 10,000 oersteds. Parameters characterizing ferrite are given in figure 1. (See fig. 9 for ε_2.)

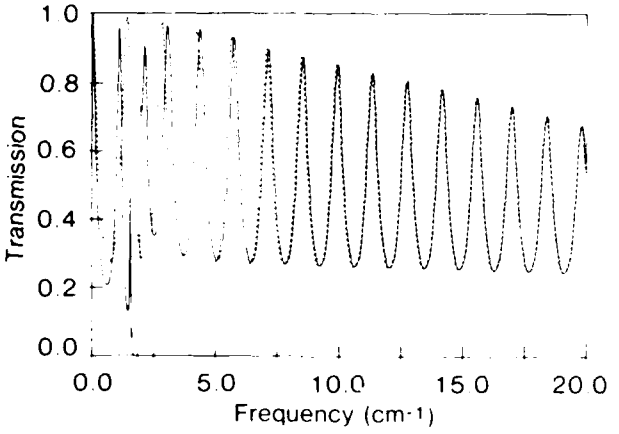

Figure 13. Power transmission coefficient ($E \parallel H_o$ solid, $E \perp H_o$ dashed) for 1-mm-thick sample. Magnetic field, H_o, is 15,000 oersteds. Parameters characterizing ferrite (TT2-111) are given in figure 1. (See fig. 9 for ε_2.)

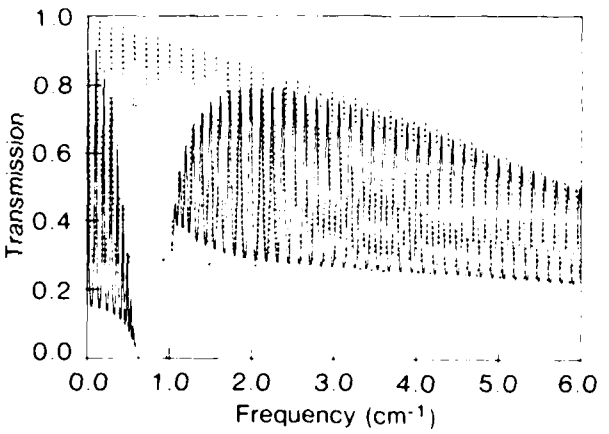

Figure 14. Power transmission coefficient ($E \parallel H_o$ solid, $E \perp H_o$ dashed) for 1-cm-thick sample. Magnetic field, H_o, is 5000 oersteds. Parameters characterizing ferrite are given in figure 1. (See fig. 9 for ε_2.)

3. DISCUSSION AND CONCLUSION

We have investigated in detail both the frequency region of ferromagnetic resonance and the region above resonance for a typical ferromagnetic material (TT2-111). In order to investigate the region near resonance with any precision experimentally, the spectrometer (or other frequency source--a stabilized source) must have very high resolution ($\Delta\bar{\nu} < \gamma\Delta H$). The ferrite chosen for many of the calculations required a field of 50,000 oersteds for resonance at ~5 cm^{-1}. This handicap can be overcome somewhat by using barium ferrite. For barium ferrite with $H_A \approx 18{,}000$ oersteds, the external magnetic field H_o is $H_o \approx 50{,}000 - H_A \sim 32{,}000$ oersteds (Van Aulock--p 464).[4] Nevertheless, some barium ferrites have a smaller ΔH than the prototype chosen here.[4] Thus, the direct measurement of the properties of these ferrites near magnetic resonance requires very high resolution ($\Delta\bar{\nu} \lesssim \gamma\Delta H/5 \approx 25$ MHz) by the spectrometer or, if the measurements are made at constant frequency, the source must have a corresponding stability.

The frequency region above resonance was examined for the possibility of meaningful measurements. The results presented here tend to indicate that the spectrometer requirements are much less stringent. Meaningful measurements can be made on ferrite material developed for the microwave region by somewhat conventional Fourier transform spectrometers.

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[4] W. H. Von Aulock, ed., Handbook of Microwave Ferrite Materials, Academic Press, New York (1965), 464.

Finally, in developing and checking the computer programs to calculate the results presented here, we are in a position to determine the experimental variables (sample thickness, external magnetic field, etc) necessary to make measurements on a particular ferrite. All that is necessary is a reasonable approximation to the real and imaginary parts of the dielectric constant and the anisotropy field, if appropriate.

Acknowledgements

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